A Decision Support System for Real-Time Management of Dissolved Oxygen in the Stockton Deep Water Ship Channel

N.W.T. Quinn [a,b], nwquinn@lbl.gov
Carl W. Chen[c] and William T. Stringfellow[a]

a. Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720
b. University of California, Berkeley, Institute for Environmental Science and Engineering, 412 O'Brien Hall, Berkeley, CA 94720
c. Systech Engineering, San Ramon, CA 95825

ABSTRACT

A decision support system (DSS) is under development to assist in the control and management of episodes of dissolved oxygen sag in a Deep Water Ship Channel (DWSC), located in Stockton, California. The DWSC was formed by excavating the bed of the San Joaquin River in the 1950's to allow navigation by ocean-going cargo ships to the Port of Stockton. The deepened channel has the effect of increasing hydraulic residence time by a factor of ten, allowing accumulation of decaying algae and other oxygen demanding substances - which creates a barrier to the migration of anadromous fish. This problem, which manifests itself in late summer and early autumn, is an impediment to a multi-million dollar habitat restoration effort for the salmon fishery in the San Joaquin River basin (SJRB). A hydrodynamic and water quality model of the Delta and San Joaquin River forms the basis of the DSS which will provide forecasts of dissolved oxygen sag in the DWSC and provide modeling support for management actions such as forced aeration to improve dissolved oxygen concentrations in the Ship Channel. A graphical user interface, currently used for displaying flow and salinity forecasts on the San Joaquin River, is being adapted to allow the display of dissolved oxygen forecasts and to encourage the formation of a stakeholder-led entity or institution to adaptively manage the problem.

BACKGROUND

The San Joaquin River Basin (SJRB) is the single most important agricultural region in the United States with an annual average production valued at more than US$6 billion. The SJRB is also the most vulnerable region in the State, given the reliance of agriculture on irrigation and the fact that many of the productive soils on the west-side of the SJRB are derived from marine shales, high in natural salts. In the past decade, recognition of the environmental harm caused by high concentrations of salts such as boron, trace elements such as selenium, and low dissolved oxygen (DO) levels in certain reaches of the River, have led to a reassessment of environmental management in the Basin. This paper describes a current research and modeling effort to assist future resource management in the basin and explains how the problems associated with low DO levels in a ship canal, excavated in the lower end of the San Joaquin near the City of Stockton, (Figure 1) can act as an integrator for other contaminant management issues.

Figure 1. Map of the San Joaquin River Basin showing the location of the Deep Water Ship Channel (DWSC) near Stockton, California.

DISSOLVED OXYGEN PROBLEMS IN THE SAN JOAQUIN RIVER

Oxygen demanding substances contributed by upstream agricultural, wetland and municipal sources combine with decaying algal biomass, produced within the San Joaquin River (Figure 2) to create a DO sag within the Stockton Deep Water Ship Channel (DWSC). The problem is compounded by a transition in hydraulic residence time as the river passes from its shallow well-oxygenated channel (approximately 30 metres wide and 3 metres deep) to the deep, wide ship channel (approximately 150 metres wide and 10 metres deep) - a transition which promotes settling of suspended material such as sediment and algae and encourages periodic water column stratification. Occasional mixing of the surface and near bottom water is provided by the passage of large ships, which berth in the ship channel, and which traverse the ship channel to the Port of Stockton Turning Basin. Residence time in the DWSC has been estimated to range between 5 and 25 days (Chen, 2002). Biodegrading algae and organic sediments in the DWSC remove oxygen from the water column and create conditions adverse to the maintenance of DO concentrations above 5 mg/l. The DO objective of 5 mg/l is a minimum level, suggested by the Environmental Protection Agency (EPA), to avoid adverse impacts to juvenile salmonids.

FACTORS AFFECTING DISSOLVED OXYGEN SAG

Dissolved oxygen in the DWSC is also controlled by factors such as stream flow within the SJR, the hydraulics of tidal, water temperature, and concentrations of various constituents known to contribute to oxygen sag including ammonia, discharged from the Stockton sewage treatment plant upstream of the DWSC, primarily during the winter months when other treatment options are less available (Chen and Tsai, 2001 - Figure 3). Phytoplankton, when living, produce oxygen during photosynthesis and consume oxygen during respiration. Photosynthesis only occurs when light can penetrate the water column - hence oxygenation of the San Joaquin River and the DWSC is dependent on turbidity as well as temperature. Mass loading of phytoplankton can be high from upper watershed sources where water is often stagnant for short periods of time and nutrient levels of nitrogen and phosphorus are in excess, leading to a build-up of aquatic plants including algae. Other potential DO sinks include local urban runoff and upstream agricultural sources including dairy farms, private and public wetlands. These factors appear to be important early in the summer whereas DO sag caused by nitrogen loading, including both ammonia and non-ammonia TKN is prevalent in the late summer and fall, based on Biochemical Oxygen Demand (BOD) and Carbonaceous BOD (CBOD) experiments (Lehman, 2001).

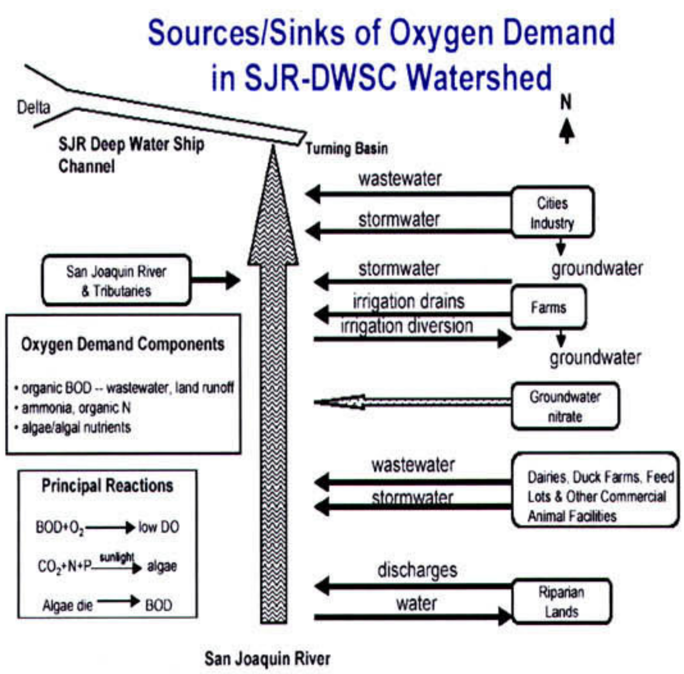

Figure 2. Sources and sinks of oxygen demand in the San Joaquin River Basin (Lee, 2002).

Oxygen production by algal photosynthesis and its consumption by bacterial respiration are usually in balance. Occasionally algal production and consumption occur at different locations in a watershed giving rise to low oxygen conditions that can block fish migration and may even result in occasional fish kills (Horne, 2001). In surface waters algae produce much more oxygen by photosynthesis than they consume via respiration. In eutrophic surface waters DO concentrations often exceed 150% of saturation. Even at night, when photosynthesis ceases but respiration continues, there is usually ample oxygen for fish and other wildlife. However, because oxygen forms bubbles at over 120% saturation, much valuable oxygen is lost to the atmosphere leaving a net deficit in the water. The controlling factors for the DO can change with time by hour, day, and season. The dynamic nature of the estuary system make it impossible to isolate a single factor can be used to explain the observed DO change, because all factors work in concert to affect the DO in the Lower San Joaquin River. Sediment oxygen demand is associated with organic matter that has accumulated in the DWSC over several years.

Temporal discrimination of load contributions among these primary sources of BOD has significant implications for the development of an equitable dissolved oxygen Total Maximum Daily Load (TMDL). The TMDL allocation process is an EPA sanctioned procedure, applied to impaired waterbodies, to ensure that the pollutant assimilative capacity of the waterbody is not exceeded, and for distributing responsibility amongst stakeholders for clean-up.

MANAGEMENT OF DISSOLVED OXYGEN SAG

Management solutions to address the Stockton DWSC problem involve : (1) recognition of the relative contribution to the problem by agricultural, wetland and municipal sources; (2) coordinated continuous monitoring of the factors contributing to low DO in the SDWSC; and (3) development of a decision support and management tool that allows forecasting of future DO conditions in the SDWSC – a tool that guides action to remedy potential oxygen deficit conditions before they occur.

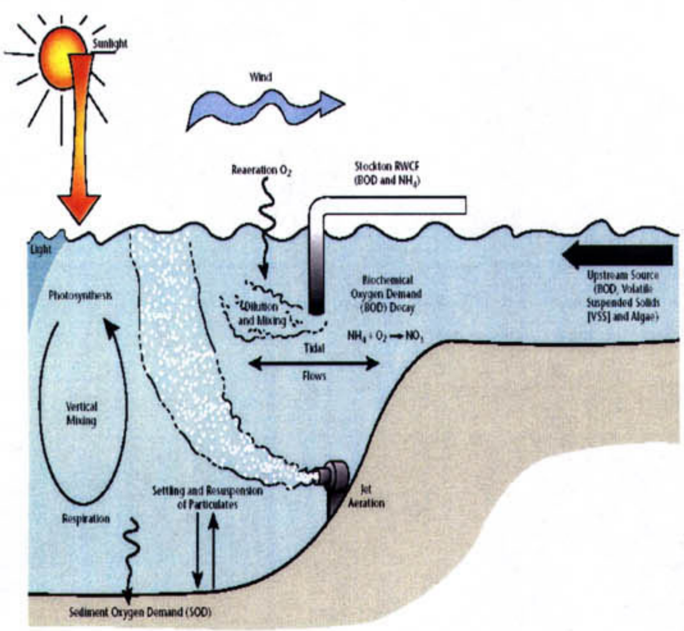

Figure 3. Conceptual model of factors affecting dissolved oxygen sag in the DWSC (Lee, 2002).

Another goal of real-time DO forecasting will be to improve coordination of activities among those entities that directly benefit from and depend on the resources of the San Joaquin River. Use of a decision support tool as a device for watershed coordination and to provide direction to a comprehensive monitoring plan has not been attempted before in the SJRB but makes sense in this instance because of the complexity of the science and the large number of stakeholders potentially affected. If the models underlying the decision support system are based on sound science they can help in the identification of key data gaps, as well as allow for the simplification of initially expensive monitoring plan, as relationships between important factors become better understood and good surrogate alternative metrics are developed. Adaptive monitoring systems need to be proactive and have the potential for effect significant cost savings for long-term environmental monitoring.

DECISION SUPPORT SYSTEM DEVELOPMENT

The development of the decision support system for DO management in the DWSC will require a long-term commitment of resources both fiscal and intellectual. An expedient to ensuring the success of this enterprise was to capitalize and add to an existing, successful salinity forecasting and management system, that has been implemented in the SJRB for the past 5 years. Although the nodal network for the existing modeling system terminates at Vernalis (a monitoring station upstream of the Stockton DWSC) the addition of nodes and additional water quality parameters downstream of the network is relatively trivial. A graphical user interface, developed by Systech Engineering Inc. (Quinn et al, 1997) for the real-time salinity management project, also has utility for the newly contemplated decision support system.

Real-time flow and salinity management

Real-time salinity monitoring on the San Joaquin River during the past 4 years (Quinn, 1999) has documented prolonged periods of poor water quality and opportunities to significantly improve SJR water quality through improved coordination of east-side reservoir releases with west-side agricultural and wetland discharges. The Real-Time Water Quality Management project (Quinn et al, 1997; Quinn and Karkoski, 1997; Quinn and Karkoski, 1998; Quinn, 1999) has established the monitoring, communications, and modeling systems needed to provide water managers with much of the information necessary to manage their discharges on a real-time basis. Real-time flow and water quality data collection and processing were conducted every week since the programs inception in April 1999. The SJRIODAY model, a daily mass balance of flow and salt load inputs and outputs to and from the River, was run weekly to provide estimates of flow, water quality, and assimilative capacity both for current conditions and for a two-week forecast.

The water quality modeling and forecasting process begins with collection of and compilation of flow and water quality data from key sites in the SJRB. Spreadsheets are used to convert these data into FORTRAN compliant text files that are used as input to the SJRIODAY model. Once the data has been preprocessed, the SJRIODAY model is run for the appropriate time period – in this case for the previous seven days and for a 14-day forecast period (Figure 4).

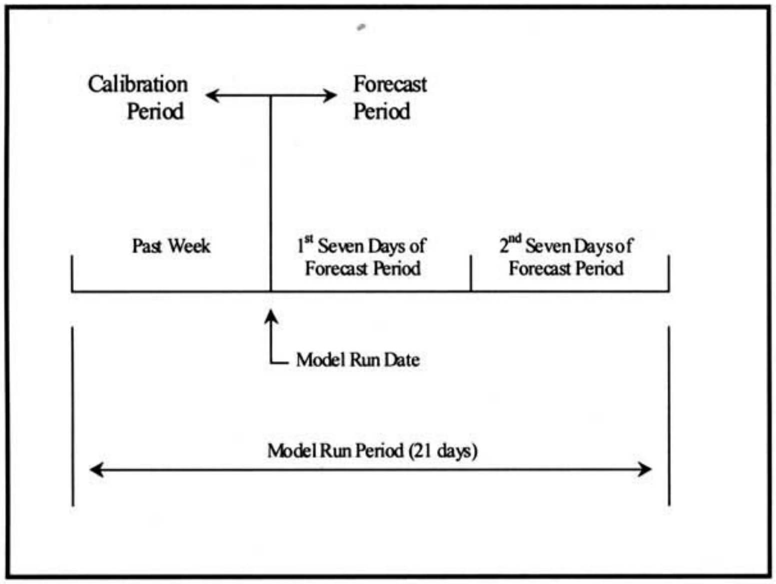

Figure 4. Structure of a typical 21-day model run using SJRIODAY.

Model output for the historical seven-day period is compared to real-time data and the model is iteratively calibrated and re-run until modeled results are within ten percent of the actual data. Calibration is achieved through adding or removing flow and salt load at user specified river reaches. The same flow and salinity adjustments made to calibrate the model during the 7-day calibration period are applied to the 14-day forecast period. The modeler must therefore use best professional judgment to decide where to make adjustments in the SJR system and to determine if a particular calibration scenario can be reasonably explained given the physical constraints of the SJR system.

Once the model has been calibrated satisfactorily, the SJRIODAY model output files are converted to web-ready HTML documents and uploaded to a public web server. E-mails are sent to notify interested parties and signatories to an interagency Memorandum of Understanding when the website has been updated with a new forecast. The real-time forecasts consist of series of tables and graphs that provide data on flow, EC, and assimilative capacity in the SJR at Crow's Landing, the Maze Road Bridge, and Vernalis. Each week the forecast also includes discussion of the model results, the major model assumptions, and the model inputs.

DISSOLVED OXYGEN MODELING

Models for DO concentrations in rivers and estuaries have existed for over a century. The mathematical and biochemical basis for DO analysis was formulated by O'Connor (1960) and Thomann (1963) who recognized that the process of stabilization of oxidizable material led to a reduction of DO in streams. Perhaps the most commonly used model for DO sag is the Streeter-Phelps equation which represents the DO response to a single point discharge of a pollutant (Thomann and Mueller, 1987).

This basic modeling approach has been advocated as the backbone of a DO monitoring and decision support system for the San Joaquin River and the estuary system. Loading estimates of all constituents and contaminants in the system rely on good flow estimates. Hence a calibrated flow model is a prerequisite to a calibrated water quality in the Basin. The current modeling effort will involve tying together two existing models one in the Estuary and the other in the SJR, each developed for different reasons using different computer codes. Work has already started to develop a single model that incorporates both the SJR and DWSC within a common model framework.

Stockton DWSC model

Chen and Tsai (2000) developed a DO model for the City of Stockton in 1993 which utilizes a link-node formulation of the San Joaquin River and South Delta. The model accounts for the solubility of DO as a function of temperature and considers sinks due to BOD decay, ammonia oxidation and algae respiration. The DWSC model was calibrated with 1991 data including real-time meteorological data, tide and waste load discharge data from the City of Stockton.

Results from the DWSC model simulations showed reasonable match to water quality observed during the months of August and September. The model generally simulated the time series of the mid-depth DO for all locations and the concentration profile of DO for specific dates. Compared to the observed data of year 2000, the mean relative error of DO prediction for mid- depth values, measured by the City of Stockton stations, was approximately 0.25 mg/l and the mean absolute error was 0.59 mg/l. For the downstream section of the DWSC, where stratification develops during hot summer days when river stage and flow is low, Systech Engineering Inc. developed algorithms that incorporate a series of vertical layers into the existing model (Chen, 2002). This layered model accounts for the vertical variation of temperature, light, particulate settling and algae growth, which can cause a vertical variation of DO in the DWSC.

San Joaquin River DO model

The Delta Simulation Model (DSM-2) is the standard tool used by the Department of Water Resources (DWR) for Estuary hydrodynamic studies. The water quality processes, sources, and sinks are similar to those used in the DWSC model. Whereas the DWSC model is based on the Euler grid that tracks the mass moving in and out of stationary nodes the DSM-2 water quality module uses a Lagrangian technique to track the mass in moving parcels of water.

The DSM-2 model has been extended by the DWR along the SJR including the lower river and its major tributaries to create the Lower San Joaquin River DO model (Rajbhandari, 2001) . The Lower San Joaquin River DO model accounts for tide, channel depth, river flow, headwater quality, sediment oxygen demand, point source and non-point source loads and can calculate various mass fluxes to support integrated data analysis and hypothesis testing. The calibrated model can be used to predict the response of DO in the river under various management scenarios of waste load reductions and river flow manipulations. The model comprises two submodels, HYDRO determines flow hydrodynamics and QUAL simulates both conservative and non-conservative constituents in the water body. To extend the SJR portion of the HYDRO submodel extensive use was made of the calibrated SJRIODAY model, described previously, to develop the DSM-2 flow calibration. The electrical conductivity calibration in SJRIODAY was also useful since it provided data on the passage of a conservative constituent such as salt through the river system and into the DWSC. As with salinity, the calculation of DO and other factors that affect DO is based on the principle of mass balance.

Different constituents will have different sinks and source terms. For conservative substances, the sink term is limited to water diversions and the source term is limited to waste discharges. For non-conservative substances, there is an additional sink term for decay. For DO, sinks and sources become more complicated. Sinks include BOD decay, ammonia nitrification, sediment oxygen demand, algal respiration, and decay of volatile suspended solid. Organic nitrogen is included in three pools (algae, pheophytin, and volatile suspended solid). When the parent pools decay, they release ammonia, which is a sink of DO. While algal respiration is a DO sink, algal photosynthesis is DO source that contributes DO to the water. The model tracks five settleable groups of particles: chlorophyll-a, pheophytin, detritus, inorganic solids, and sand. Chlorophyll-a is live algae; pheophytin is dead algae; detritus is land derived organic matter; and inorganic solid is fine silt or clay. Each group settles to the bottom according to their settling velocities. The model assumes that settled algae become pheophytin. For that reason, the model accumulates only four groups of sediment: pheophytin, detritus, inorganic solid, and sand.

The model is driven by the boundary conditions and a set of model coefficients. For each simulation, specific data of river flow, meteorology, tide, Stockton wastewater treatment plant discharge and upstream water quality concentrations are supplied. The model simulates the dynamic variations of flow and water quality along various reaches of the San Joaquin River. The model predictions are compared to the observed values in time series and concentration profiles.

Preliminary results of simulations

In the calibration performed the DO deficit was most sensitive to river load, river flow, and Stockton load, in that order. A 5% increase in river load was shown to increases the DO deficit by 50%. A 10% increase in river load increased the DO deficit by 185%. A 5% decrease in river load decreases the DO deficit by 34%. A 10% decrease in river load decreases the DO deficit by 76% (Rajbhandari, 2001). River flow, river load, and Stockton wastewater treatment plant load are key control measures to solve DO defecit in the DWSC. At a low flow of 7 cubic metres/second, the DWR modelers found that no reasonable reduction of treatment plant load and/or upstream loads could help raise the DO above 5 mg/l (Rajbhandari, 2001). At a high flow of 50 cubic metres/second, reasonable reductions of treatment plant load and the river load could meet the DO objective. Analysis showed that the DO deficit would disappear if the DWSC were eliminated and the San Joaquin River were returned to its historic water depth of 2.5 metres. Model simulation also showed that deepening the channel was, in part, responsible for a deterioration of DO due to increase of residence time

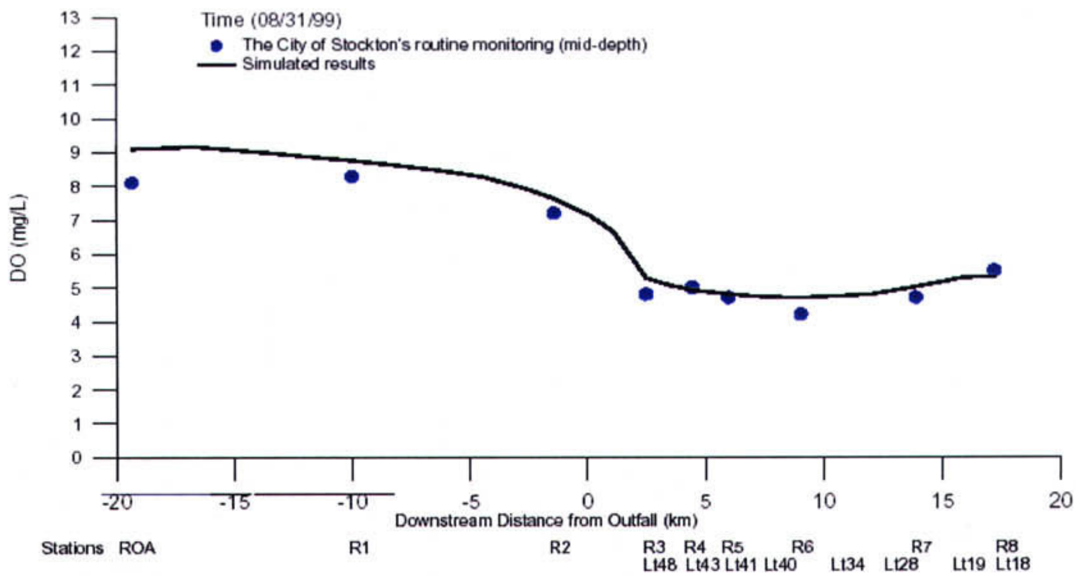

Figure 5. Calibration results from the Chen and Tsai dissolved oxygen model for the DWSC (Chen and Tsai, 2000).

DATA HANDLING AND STORAGE

The purpose of real-time forecasting of DO and salinity in the SJR is to improve coordination of activities among those entities that directly benefit from and depend on the resources of the SJR system leading to an overall improvement in river water quality. Forecasting relies on monitoring and modeling - improving automation and cost effectiveness of data collection and coordinating modeling activities to provide positive feedback to help evaluate monitoring system design. A Technical Advisory Committee was established for the project to promote free exchange of information between participating agencies and independent researchers. A project relational database, accessible through a data browser, has been established and database templates designed for the agency and independent research teams to allow seamless integration with the master project database. The project database contains both discrete and time series data sets and is supported by customized analytical tools to allow location mapping within a geographic information system (Arc-Info) and parsing into formats required for the DSM-2 San Joaquin River hydrodynamic and water quality model.

Use of the internet will be expanded to providing timely forecasts of SJR water quality to stakeholder groups and to encourage involvement by all affected and contributing communities in water quality monitoring. It has been observed in related projects that water districts will cost-share monitoring projects if provided ready access to their own data. In the increasingly contentious water disputes that have become commonplace in California, a state with 10% of the US population, scientifically defensible data is considered an asset to combat agency regulation and hostile litigation. One of the project stakeholders is the Grassland Water District whose salinity adaptive management project has a website that attempts to provide private landowners and duck club operators with current information on best management practices (obtained from one of the project sites) that can reduce discharge to the River at critical periods for downstream water quality.

STAKEHOLDER COMMUNICATION

An important element of real time water quality management is to communicate rapidly with stakeholders about the model forecast of impending DO violations and to allow simulation of the effects of potential remedial measures that may be undertaken to avoid these events. Examples of these measures include the operation of hydraulic barriers upstream of the DWSC, drainage reuse and recycling in agricultural water districts and adjusting the timing of wetland water return flows to the SJR. Web sites have been created for the stakeholder process, through which these individuals can login, see a calendar of events, request model runs, and view model results in graphs, superimposed on GIS maps. Figure 5 is a screen capture from an actual forecast in July of 2000 for the SJRIODAY model which demonstrates the configuration of the system currently used for salinity forecasting which will be enhanced to include additional water quality parameters of concern for DO modeling.

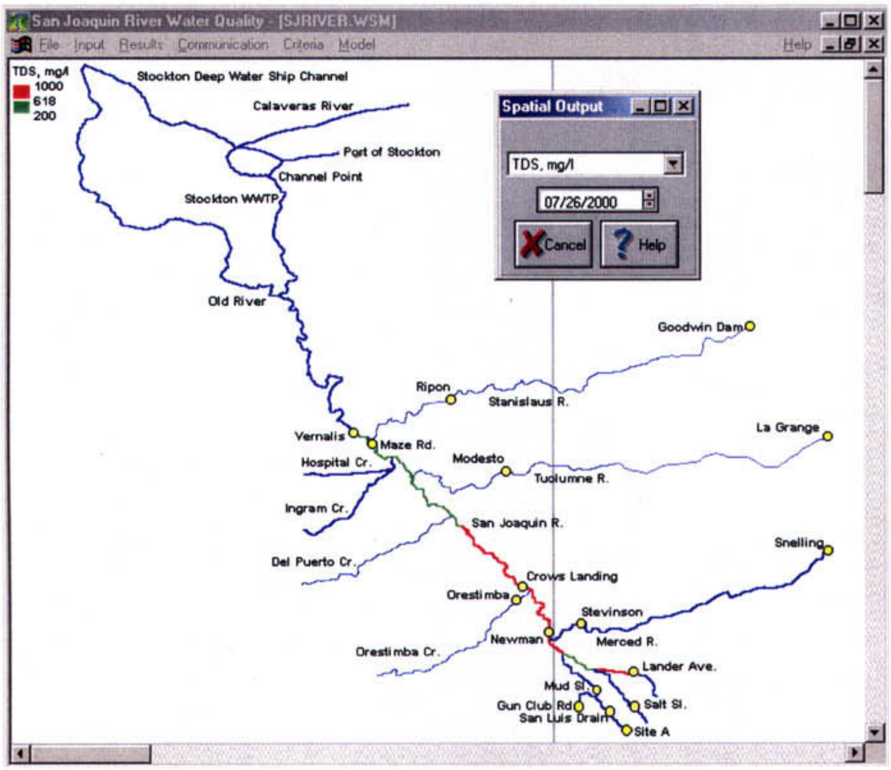

Figure 5. User interface from the SJRIODAY salinity forecasting project adapted to be used for SJR DO forecasting.

PROJECT OUTCOME

The project will expand use of the internet by providing timely forecasts of San Joaquin River DO water quality and will strive to involve all affected and contributing communities in water quality monitoring. Automation where possible and the use of shared databases for enhancing communication between current monitoring and environmental restoration projects will result in improved technology transfer and will improve the likelihood that these initiatives will be continued after the current project term has expired. The goal of all watershed projects should be self-sufficiency - whereby government funding provides resources to overcome initial inertia and obtain evidence of real community benefit after which the local community finds ways to support at a minimum those aspects of the project that are likely to provide a positive benefit stream.

ACKNOWLEDGEMENTS

The authors would like to thank the International Symposium on Environmental Software Systems technical review panel for reviewing and providing comments on this paper.

REFERENCES

Chen C.W. and W. Tsai, 2000. Rough loading calculation for dissolved oxygen sinks in the lower San Joaquin River, Project Report, Systech Engineering Inc., San Ramon, CA.

Chen C.W. 2002. Proposal for a 2-D version of the Systech Stockton Dissolved Oxygen model. Systech Engineering Inc., San Ramon, CA.

Horne, A. J. 2001. Prevention of fish kills by oxygenation. Testimony to the US Senate Energy Sub-Committee, April 2001.

Lee G.F. 2002. Draft Synthesis Report for the CALFED 2001 San Joaquin Low Dissolved Oxygen Studies.

Lehman P., 2002. Oxygen demand in the San Joaquin River Deep Water Channel, fall 2001. CALFED 2001 San Joaquin Low Dissolved Oxygen Studies.

O'Connor D.J. 1960. Oxygen balance of an estuary. American Society of Civil Engineering, J. Sanitary Engineering Div. 86(SA3): 35-55.

Quinn N.W.T., C.W. Chen, L.F. Grober, J. Kipps and E. Cummings. 1997. Computer model improves real-time management of water quality. California Agriculture, Vol. 51, No. 5.

Quinn N.W.T. and J. Karkoski. 1997. Prospects for real time management of water quality in the San Joaquin River Basin, California. Lawrence Berkeley National Laboratory Report, LBNL-40513, Earth Sciences Division, Berkeley, California.

Quinn N.W.T. and J. Karkoski. 1998. Potential for real time management of water quality in the San Joaquin Basin, California. American Water Resources Association, Vol 34, No. 6.

Quinn N.W.T. 1999. Real time management of water quality in the San Joaquin Basin, California. Environmental Software Systems. Environmental Information and Decision Support, 3rd ISESS conference August 30-September 2, 1999, Dunedin, New Zealand. Edited by: Ralf Denzer, David A. Swayne, Martin Purvis and Gerald Schimak. Kluwer Academic Publishers, Massachusetts.

Rajbhandari, H.L. 2001. Dissolved Oxygen and Temperature Modeling using DSM2. Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh. 22nd Annual Progress Report to the State Water Resources Control Board. California Department of Water Resources. Sacramento, CA.

Thomann R.V., 1963. Mathematical model for dissolved oxygen. American Society of Civil Engineering, J. Sanitary Engineering Div. 89 (SA5) : 1-30.

Thomann R.V. and J.A. Mueller, 1987. Principles of surface water quality modeling and control. Harper-Collins.